

**Feasibility Study of Velocity and Temperature Measurements
of an Arcjet Flow
Using Laser Resonance Doppler Velocimetric (LRDV) Technique**

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ABSTRACT

Thermal protection system (TPS) materials are used in space vehicles to shield from high heating environment encountered during their atmospheric reentry.¹ Arcjet wind tunnels are used to simulate the flowfield encountered by the spacecrafts, and are used for testing TPS materials. How well these tests simulate the actual heating environment encountered by space vehicles depends on the characteristics of the simulated flow. The flow characterization requires the determination of temperature, concentration, and velocity of the various atomic and molecular species present in the flow. However, determining these parameters requires a complex set of both analytical and experimental procedures. The ability to properly simulate the flight environment is directly related to the accuracy with which these techniques can be used to define the arcjet flow.

Laser resonance Doppler velocimetric (LRDV) technique can be used to accurately determine the velocity and temperature of a gaseous species.^{2,3} In this technique, the medium is probed with a laser beam that is in resonance with an absorbing transition of the species. The absorption lineshape is Doppler-shifted due to the flow velocity of the species, and the frequency-shift is detected as the variation in intensity of the fluorescence emitted by the species. Thus a measurement of the Doppler shift and the width of a spectral line can give both the temperature and the velocity of the flowfield.

This summer, our project was to make a feasibility study to set up an experimental arrangement for the laser resonance Doppler velocimetric technique using a ring dye laser. Experiments required troubleshooting, cleaning, testing, and alignment of two lasers and several diagnostics instruments. All instruments and lasers necessary for the project worked well, but the output power of the broadband fundamental dye laser was limited to about 20 mW. This was quite low as compared to that necessary to obtain second harmonic oscillation at 327.49 nm for the LRDV studies. Further optimization of the dye laser optical elements is necessary before it can be used for the experiment, which requires narrowband (about 20 Mhz) laser operation.

BACKGROUND

Introduction

Thermal protection system (TPS) materials are used in space vehicles to shield from high heating environment encountered during their atmospheric reentry.¹ Arcjet wind tunnels are used to simulate the flowfield encountered by the spacecrafts, and are used for testing TPS materials. How well these tests simulate the actual heating environment encountered by space vehicles depends on the characteristics of the simulated flow. The flow characterization requires the determination of temperature, concentration, and velocity of the various atomic and molecular species present in the flow. However, determining these parameters requires a complex set of both analytical and experimental procedures. The ability to properly simulate the flight environment is directly related to the accuracy with which these techniques can be used to define the arcjet flow.

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Theoretical

The shift in the absorption line center is given by²

$$w_s = w_o \left(1 \pm \frac{\bar{v}}{c} \right) \quad (1)$$

where w , is the shifted absorption frequency, w_0 is the absorption frequency at rest, \bar{v} is the velocity of the absorber with respect to the direction of the light propagation vector, and c is the speed of light. In a gas with a random velocity distribution, the lineshape arising due to Doppler broadening is:

$$I(w) = I_0 \exp \left[-4 \ln 2 \left(\frac{w - w_0}{\Delta w_D} \right)^2 \right] \quad (2)$$

where Δw_D is the characteristic Doppler width and is given by

$$\Delta w_D = \frac{w_0}{c} (8RT \ln 2 / M)^{1/2} \quad (3)$$

where R is the universal gas constant, T is the temperature, and M is the molecular weight of the gaseous species.

Under most practical arcjet flow measurement conditions the Doppler effect provides a major contribution to the linewidth than the natural and collisional broadening. Thus, in principle, measurement of the Doppler shift and the width of a spectral line can give both the temperature and the velocity of the flowfield.

Copper Atom as a Probing Species

The anode of the dc arc column of the arcjet is made of copper and the sputtered copper in the flow field is found to be sufficient to carry out LRDV studies. The spectroscopy of atomic copper makes it an ideal candidate for flow velocity and temperature measurements. The ground

state of the Cu atom is the $^2S_{1/2}$ state. The optically allowed absorptive transitions to the energy states $^2P_{3/2}$ and $^2P_{1/2}$ occur at wavelengths 324.85 and 327.49 nm respectively. Radiative decay from the $^2P_{3/2}$, $^2P_{1/2}$ states to the metastable states $^2D_{5/2}$, $^2D_{3/2}$ gives emissions at 510.70 and 578.37 nm respectively. This is illustrated in an energy level diagram in Fig.1. Doppler width and frequency shift measurements may be accomplished by exciting the 2P - 2S transition with a narrow band dye laser and scanning the frequency of the dye laser to find the line center and width. The fluorescence emitted from the 2P state is proportional to the fraction of the excitation beam absorbed. But the analysis of the lineshape is complicated by the hyperfine splitting of the energy levels. The problem can be simplified by exciting only the $^2P_{1/2}$ - $^2S_{1/2}$ at 327.49 nm, where only two hyperfine components in each level are involved. In this case, only the $^2P_{1/2}$ - $^2D_{3/2}$ emission line at 578.37 nm is observed. A more detailed energy level diagram for these transitions is shown in Fig.2.

Arepalli et al.³ demonstrated the feasibility of the LRDV technique using a pulsed dye laser and a heated cell containing copper vapor as the absorbing medium. The accuracy of velocity and temperature measurements of the flow field can be improved by using a narrowband pump laser such as a ring dye laser that can be used to resolve the hyperfine splitting in the Cu atom spectral lines mentioned above. This summer, our project was to make a feasibility study to set up an experimental arrangements for the laser resonance Doppler velocimetric technique using a ring dye laser.

EXPERIMENTAL

The objective of the project was to set-up the ring dye laser at the excitation wavelength of 327.49 nm as required for the Cu atom study and characterize its frequency bandwidth. The experiment could be divided into several parts: (i) troubleshooting, and setting up the pump argon ion laser, (ii) troubleshooting, cleaning, and setting up the dye circulator for the dye laser, (iii) mixing of DCM dye with benzyl alcohol to obtain oscillation at the frequency-doubled wavelength of 327.49 nm, (iv) alignment and optimization of the dye laser without the intracavity elements to obtain broadband emission at the fundamental wavelength around 655 nm, (v) optimization of the dye laser output with intracavity etalons and tuning elements to obtain narrow bandwidth and second harmonic oscillation at the required 327.49 nm, (vi) troubleshooting and setting up the spectrum analyzer with a HeNe laser, and finally (vii) characterize the dye laser oscillation bandwidth using the spectrum analyzer. Some parts of the experiments went well in the limited time of the summer program. Others need to be continued. They are described below.

Setting Up the Argon Ion Laser

The argon ion laser was not in operational condition, and it was found that the water flow control switch was not working. A new flow switch was purchased and it was installed in a separate socket, so that it can be changed easily in the future. This was not possible before. With this simple change, the laser was found to be operational with an output power of more than 6W (multi-wavelength operation), which was necessary for the dye laser pumping.

Setting Up the Dye Circulator

First, the old Rhodamine 6G dye mix was poured out safely and the dye circulator was cleaned as per standard operating procedure ES4-SOP-ARMSEF-129.0. Then it was circulated several times with methanol and ethylene glycol until no trace of old dye was present. The dye jet at the laser head was also cleaned so that a thin ribbon like flow was present at the jet. For the new dye solution, 2 grams of DCM was mixed with 400 ml of benzyl alcohol and the mixture was vigorously mixed for about an hour in a soner bath. Most of the mixture was poured in the circulator for dye pumping. The leftover would be added later to optimize dye laser output power.

Oscillation of Dye Laser Without the Intracavity Optical Elements

First, the dye laser oscillation was tried without the complex intracavity optical elements as per procedure described in the operation manual of the ring dye laser (Coherent 699-05 ring dye laser). These elements include, nonlinear crystal for second harmonic generation, birefringent filter for frequency tuning, and a cascade of etalons for extreme narrow band operation. See Fig.3 for details. For initial alignment of the laser, the pump argon ion laser was used at a low power (about 500 mW). The experimental arrangement is shown in Fig.4. After several foldings through high reflecting mirrors, the pump beam passed through the optic axis of the dye laser and on to the pump mirror of the dye laser. See fig.3(b). The dye circulator was turned on and the dye flow was set at 40 psi. Fluorescence emitted from the dye was used to line up the three cavity mirrors of the ring dye laser. Two counterpropagating beams of the ring were overlapped at the output coupler. The spots were further lined-up on a distant screen from the output coupler. The laser was found to be oscillating after several trials, specially after adjusting the output coupler

and the pump mirror horizontal and vertical adjustments. The output power was limited to about 20 mW. This was very low compared to the manufactured suggested power level of 300 mW. Note that we needed high power in the fundamental wavelength so that the power in the frequency-doubled wavelength would be few milliwatts, which would be sufficient for LRDV studies. But after many many tries, no further improvement in the output power of the laser was observed.

Testing of the Spectrum Analyzer

Even though the frequency-doubled output of the dye laser could not be tested for spectral analysis, but we have tested the responsivity of the spectrum analyzer using a HeNe laser as a narrowband source. The experimental arrangement is shown in Fig. 5(a). Laser beam was focused on to the spectrum analyzer (a confocal Fabry-Perot cavity) using a mode matching lens ($f = 50$ cm). The output from the spectrum analyzer was directed to an oscilloscope. To study sepectral output of the laser, the spectrum analyzer was swepted using an external sweeping generator at a sweep frequency of about 25 Hz. Figure 5(b) shows a reproduction of the oscilloscope trace observed for such a sweep. Figure shows two complete sweeps over the gain bandwidth of the laser. From the knowledge of the free-spectral range of the spectral analyzer (6 Ghz), a cavity mode spacing of 780 MHz was measured for the HeNe laser. This is equivalent to a laser cavity length of 20 cm, which was exactly measured for the laser cavity used in the experiment. Note, the neighbouring low intensity modes, at a separation of 45 MHz from the peak cavity modes, are due to transverse modes of the laser. From the figure it should be clear that the resolution of the spectrum analyzer is better than 22 MHz.

CONCLUSION

We made a feasibility study to set up a high resolution laser resonance Doppler velocimetric (LRDV) experiment to study velocity and temperature of the flowfield of an arcjet. Experiment required troubleshooting, cleaning, testing, and alignment of two lasers and several other diagnostics instruments. All instruments and lasers necessary for the project worked well, but the output power of the fundamental dye laser wavelength was limited to about 20 mW. This was quite low as compared to that necessary to obtain second harmonic oscillation at 327.49 nm for the LRDV studies. Further optimization of the dye laser output power is necessary before it can be used for the experiment.

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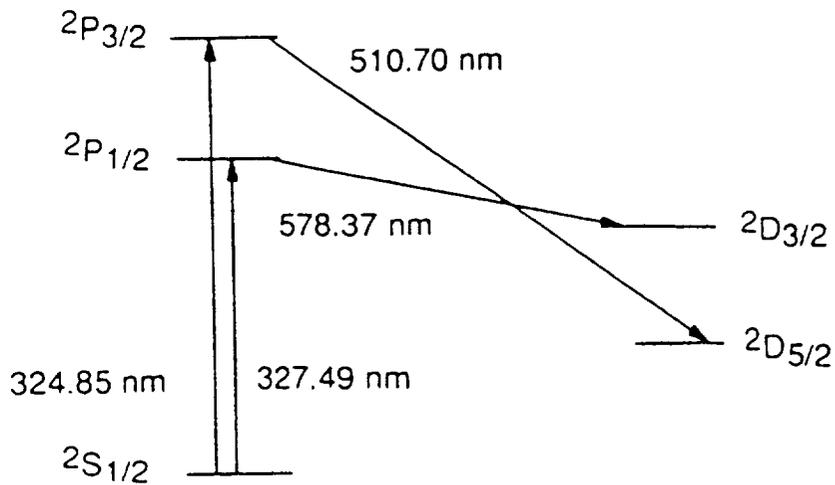


Figure 1. Energy Level Diagram Showing the Excitation from the Ground State of Cu to the Excited $2P_{1/2}$, $2P_{3/2}$ States and Fluorescence to the $2D_{5/2}$, $2D_{3/2}$ States

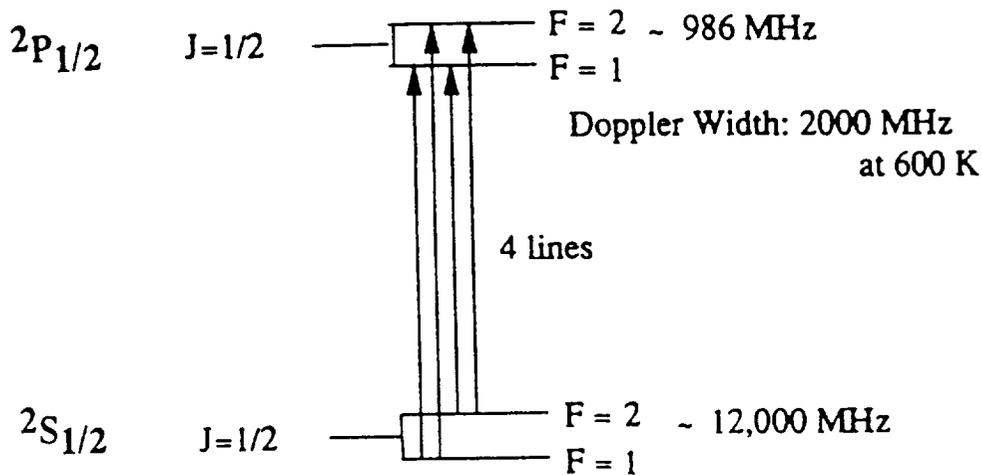


Figure 2. Detailed Level Diagram of the $2P_{1/2} - 2S_{1/2}$ Transition Indicating the Hyperfine Splittings (F sublevels)

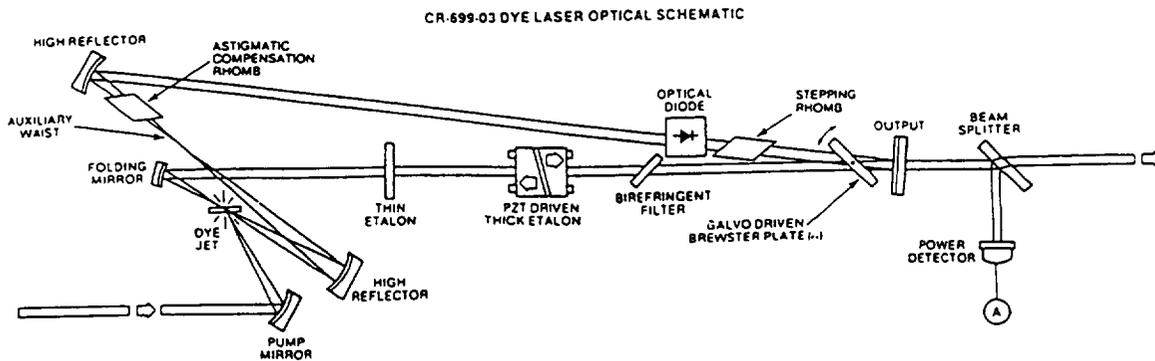


Fig. 3(a). Optical schematic of the dye laser with all optical elements.

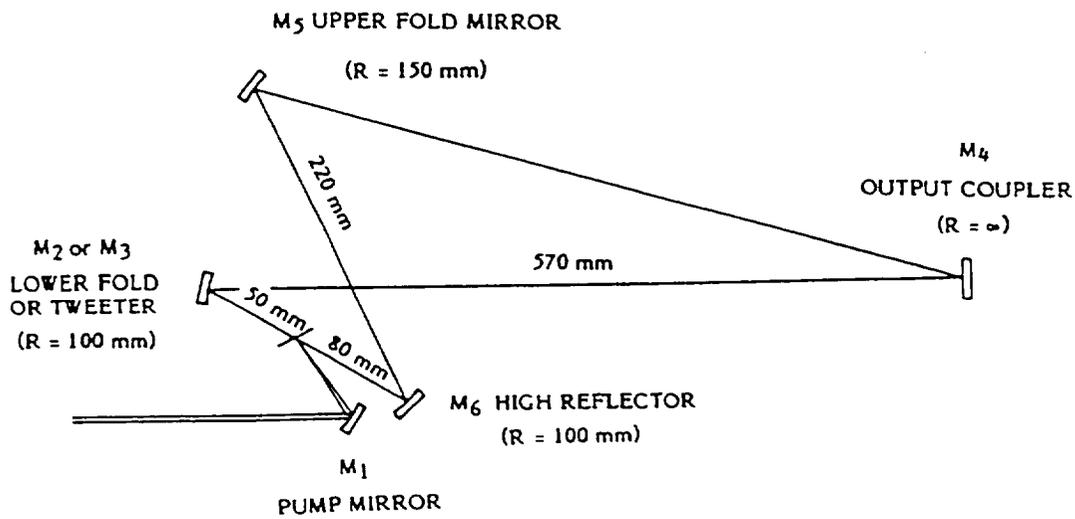


Fig. 3(b) Dye laser optical schematic without the tuning elements.

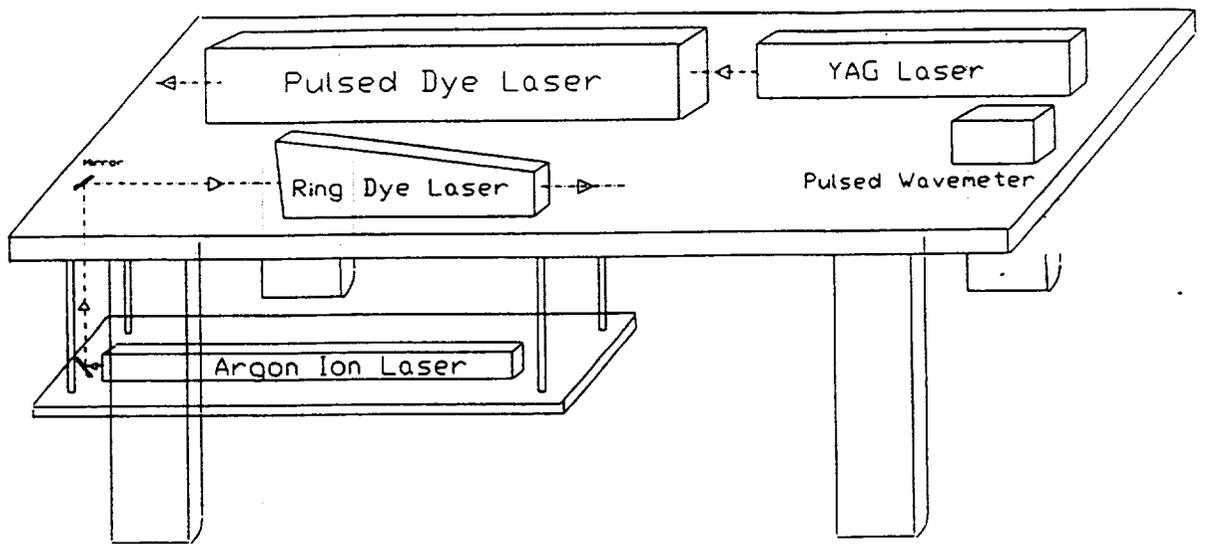


Fig.4. Dye laser pumping arrangement using an argon ion laser.

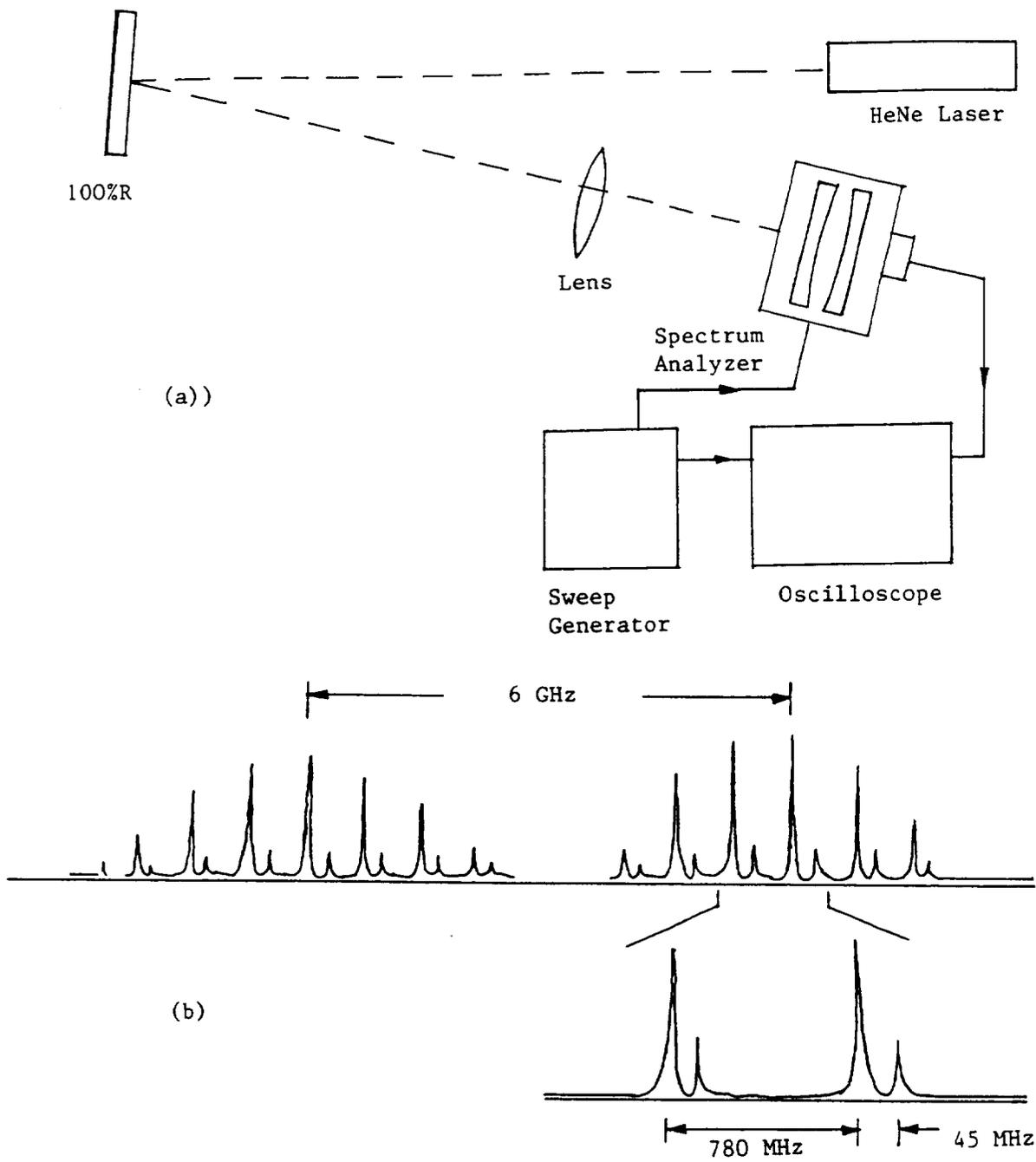


Fig.5. (a) Experimental arrangement to study resolution of the spectrum analyzer,
 (b) HeNe laser emission spectra over two free-spectral range of the spectrum analyzer.

